Institut für Plasmaphysik
KERNFORSCHUNGSANLAGE JÜLICH
des Landes Nordrhein-Westfalen

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von

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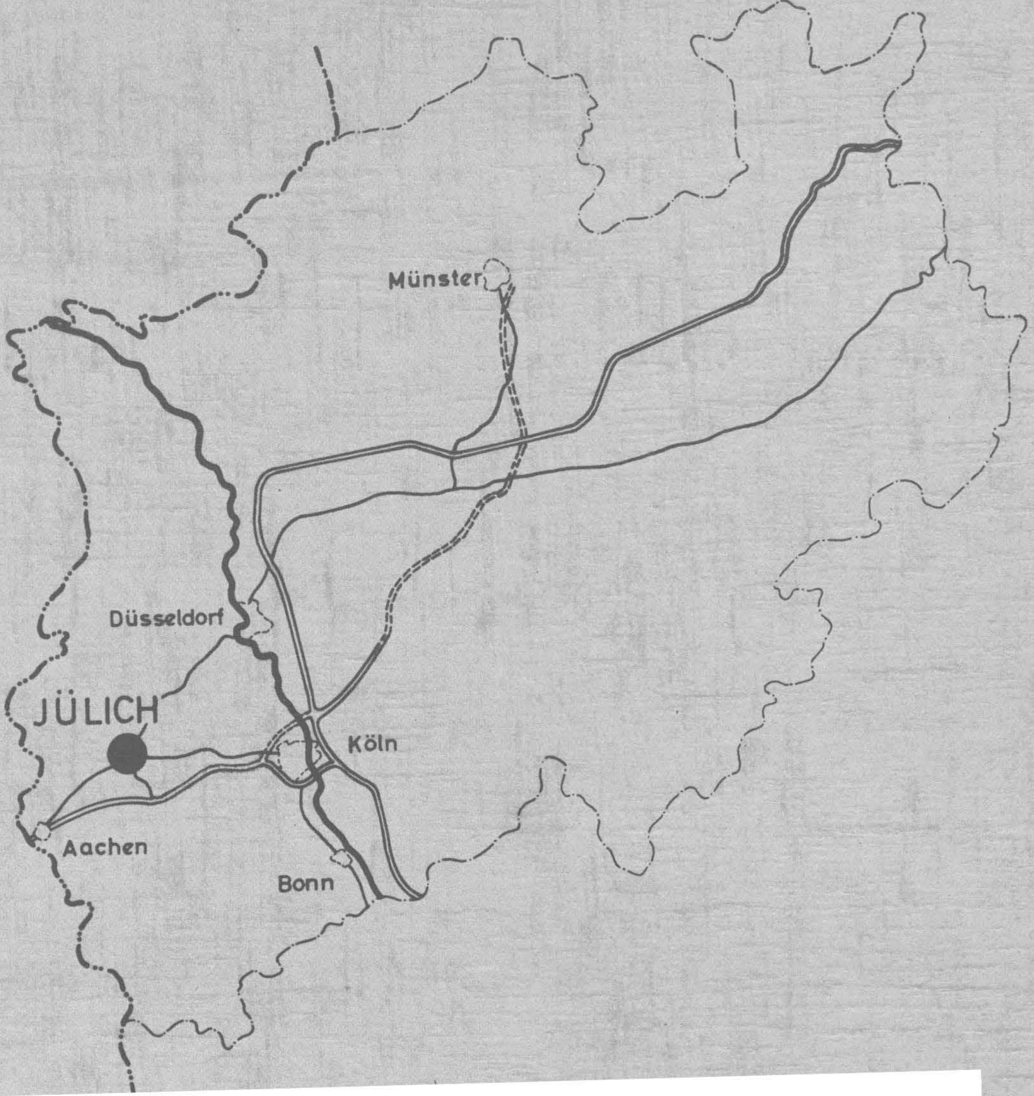
Jül - 13 - PP

August 1961

Als Manuskript gedruckt



Berichte der Kernforschungsanlage Jülich – Nr. 13

Institut für Plasmaphysik Jül – 13 – PP

Dok.: MAGNETIC FIELDS-MEASUREMENT * DK 621.317.42
PLASMA-MAGNETIC COMPRESSION DK 621.039.6

Zu beziehen durch: ZENTRALBIBLIOTHEK der Kernforschungsanlage Jülich
Jülich, Bundesrepublik Deutschland

Magnetic Field Measurements during the Fast Magnetic Compression of a Preheated Deuterium Plasma and their Relevance.

by

E. Hintz*

1. Introduction

During the last three years the possibility to produce a high density, high temperature plasma by the fast magnetic compression of a preheated plasma has won condiderable interest. The techniques for this type of experiment have been further developed, and extensive measurements have been made, mainly concerning the radiation of the plasma. Valuable information, in particular on the electron temperature and the variation of the electron temperature with time (1), and on the ion temperature (2) was accumulated. There have also been many attempts to measure the internal magnetic field and, if possible, the distribution of this internal field along a diameter of the plasma cylinder. This is of particular interest, since all observations show that an initial reverse field (3) is of great influence on the behaviour of the plasma and because there are

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some obscurities about the dissipation mechanism of the energy of the trapped reverse field. Reliable probe measurements could help to clarify this dissipation mechanism. In addition one could obtain the pressure distribution and the $\beta = \frac{nkT}{B_z^2/2/\mu_o}$ of the plasma.

It would furthermore be possible to obtain information on the stability of the plasma cylinder and on eventually developing turbulence.

So far all probe measurements in theta pinch devices have been considered as unreliable. There have been mainly the following objections:

1) Mechanical effects of the probes.

Density changes in a hot plasma are connected with changes in magnetic flux density. The probe may perturb the flow field of the plasma and thereby cause density changes, e.g. by reflection, generation of vortices and turbulence, which result in irregular fluctuations of the B-field.

2) Heat effects of the probe.

The plasma interacts with the protecting tube of the probe and is therefore cooled in the vicinity of the probe. In addition heavy ions are knocked out of the wall and contaminate the plasma. This causes enhanced energy losses and field diffusion.

3) Electrical effects of the probe.

Due to the presence of the probe a bore with zero conductivity exists in the conducting plasma cylinder. The external field penetrates through this hole and modifies the original field distribution.

During the experiments on the fast magnetic compression of preheated plasmas in our laboratory the performance of reliable magnetic field measurements has been pursued with special interest (4). Some results are communicated in this paper and will be discussed in connection with the points mentioned before. It seems to be sure that the measurements are reliable. Therefore conclusions on the state of the plasma at maximum compression and on the behaviour of the plasma during compression, in particular concerning flux conservation and particle conservation, can be drawn.

2. Experimental Arrangement.

A) General Characteristics of the Experiment.

The discharge circuit used is shown in Fig.1. L_c is the inductance of the compression coil. Two capacitor banks are connected to this coil. First F_1 is fired and an alternating magnetic field with a frequency of 900 kc per sec and a maximum amplitude of 5 000 Gauss is generated in the coil. The gas in the discharge tube has already been preionized by a 500 Watt, 10 mc per sec RF generatro, which is coupled to the discharge tube capacitively. The preionized gas breaks down, an electrodeless ring discharge starts and within 2-3 microseconds a plasma is formed. Spectroscopic measurements show that in a pressure range from 50 to 500 micron temperatures of about 20 000 degree Kelvin are achievable. The plasma is highly ionized, the impurity content is low and only determined by the leakrate of the vacuum system (5). The properties of the plasma are highly reproducible in time. The field distribution in the plasma cylinder is known with some accuracy, and the maximum amplitude of the magnetic field can be varied, either by varying the time between the start of the preheating pulse and the main compression pulse or by using a third bank for the generation of a steady magnetic field.

The main bank, consisting of 30•0 , 5 μF capacitors, charged up to 24 kV, can be fired after an arbitrary delay with respect to the start of the preheating discharge. The maximum field of the compression pulse is 46 500 Gauss, the risetime to maximum amplitude 0·9 μ sec and the maximum E_θ = 1·5 kV per cm. The bank is discharged through a single turn, cylindrical compression coil of 15 cm length and 4 cm inner diameter. The design of the coil is determined by four requirements:

1) the probe has to be inserted radially into the coil, so that the total surface of the probe in contact with the plasma is small. This involves, that the discharge tube has a pipe for introducing the probe. The coil must therefore consist of two demountable halfcylinders.

2) There is a radial magnetic field gradient at the feedpoint, where the coil is connected to the collector plate. The asymmetry in the magnetic pressure distribution is partly compensated by a corresponding gap at the opposite side of the coil. It is thereby hoped, that the axis of the plasma cylinder and of the coil coincide.

3) Measurements of the radial magnetic field distribution with the probe in various parts of the coil (e.g. inside or end position) can be made with a fixed probe position, which means without breaking the vacuum and without re-adjusting the probe. This can be arranged by interchanging the coil parts according to fig.2.

4) Arcing at the contact points has to be avoided, because this would produce nonuniformities in the field distribution.

Fig.2 shows the construction of the coil. The copper beryllium clamp acts as a spring and makes a reliable line contact for the current. This part of the design has been especially tested by discharging a 10 kjoule bank on a coil of 5 cm length and 4 cm diameter.

The magnetic probe shown in fig.2 is used for measurements discussed in connection with fig.13.

Inside the coil is a quartztube of 4 cm outer diameter, 2 mm wall thickness and 600 mm length. Fig.3 gives a total view of the experimental arrangement.

B) Magnetic Field Probe and Probe-adjusting Device

In order to keep the zero conductivity bore in the plasma cylinder small and, what is even more important, to make the contact area between the probe protecting tube and the plasma small, the total diameter of the probe should be as small as possible. On the other hand the probe should withstand a larger number of discharges. There is no difficulty in making the pick up coil small, typical values are: 0·5 mm length and 0·4 mm diameter. However there is a problem to insolate the coil from the plasma by a sufficiently thin protecting tube. In most cases quartz or ceramic tubes were used. However if the wall thickness of these tubes is small (of the order 0·1 mm) the tubes are destroyed in one discharge. A better material is stainless steel with a low conductivity and a permeability near to 1. For the use of the probes with discharges of short duration steel offers the special advantage that the mass number of the Fe-ions is high and the mobility therefore is low.

For the probes, used here, steel with a resistivity of $70\ 10^{-6}\ \Omega$ cm was chosen. With a wall thickness of 0·13 mm an estimate of the magnetic field penetration time, which limits the time resolution of the probe, gives $3 \cdot 10^{-8}$sec (7). Space resolution is of the order 1 mm. However for the intended applications one must bear in mind that in a plasma, moving with a velocity v, space resolution is of the order $v \cdot \Delta t$, where Δt denotes the time resolution of the probe.

The thickness of the bottom plate of the steel tube should be comparable to the thickness of the wall.

A probe of this type was built and is shown in fig.4. The probe is shielded from electrical stray fields and was therefore constructed in an asymmetric way. The induced voltage is then measured against ground and only one amplifier is needed for the oscilloscope, in contrast to the symmetric center tapped probe shown in fig.2.

The maximum $\dot{B}$ gives a signal of about 10 V at the oscilloscope, the maximum B a signal of about 0.1 Volt.

The probe adjusting device is shown in fig.5. The two main parts are the metal bellows A and B. A serves simultaneously as a spring and as an element movable under vacuum. B decouples the adjusting device from the discharge tube. The probe is connected to the adjusting device with a vacuum tight plug, thus being easily exchangeable.

C) Streak Camera

A 339 B Beckmann and Whitley streak camera was used to observe the variation of the plasma radius with time. The maximum time resolution of the camera is 5 m /usec at a slit width of 0·075 mm. With the experiments described here a slit width of 0·15 mm was used, which corresponds to a time resolution of $1 \cdot 10^{-8}$ sec at 2 600 r.p.s. The focal length of the objective is 300 mm and the depth of focus was about 1 cm. This is of some importance for space resolution in end-on pictures. Pictures of the plasma cylinder were taken both end-on and side-on with the slit normal to the tube axis.

3. Experimental Results

In order to get information on the properties of the plasma and on the dynamic behaviour of the plasma cylinder by magnetic field measurements, it is necessary that the state of the plasma and the distribution of the magnetic field as a function of time are well reproducible. This means specifically that the current pulse for the compression of the plasma, the distribution and maximum amplitude of the initial magnetic field and important plasma parameters such as particle density, degree of ionization and electron temperature at the start of the compression have to be highly reproducible.

These requirements have been met, details on the technical procedure will be published soon. Fig.6 shows the reproducibility of the probe signals at various days. In order to obtain this high degree of reproducibility it was essential that every new tube was cleaned up by about 30 discharges. Photoelectric records of a CV line show then also a satisfactory reproducibility.

The diameter of the probe being 1 mm, the original field distribution should not be modified too much by the presence of the probe if the diameter of the plasma is about 10 mm. At an initial pressure of 250 μ D_2 and with a delay of about 3 μsec between preheater and main discharge the measured minimum diameter of the plasma is 8 mm, corresponding to a cross sectional area of about 50 mm^2 of the plasma, while the projection of the cooling area of the probe is 4 mm^2. All measurements described here have been made under these conditions.

Streak photographs show that the velocity of the plasma boundary during the shock phase is about 10^7 cm sec^{-1}. At these velocities time and space resolution of the probe are not sufficient to measure the spatial distribution of the magnetic field. During the adiabatic stage the oscillation amplitudes of the plasma cylinder are very low. Therefore near current maximum it should be possible to resolve the magnetic field distribution and thereby measure the ß of the plasma.

On the other hand reliable measurements of the magnetic field as a function of time should be performable on the axis, because there the radial flow velocity of the plasma is always zero and perturbations of the internal field by magnetic fields penetrating from outside are very low.

For both cases the possible cooling effect of the probe on the plasma must be especially examined.

The dynamic behaviour of the plasma, such as periods and amplitudes of oscillations of the plasma cylinder, should be influenced by a strong contamination of the plasma by heavier ions. Due to the decreasing conductivity the flux is then no longer constant. Therefore streak camera photographs of the plasma with and without probe should show differences if the probe disturbs the plasma strongly. Fig.7 shows streak photographs of the plasma with and without probe. Differences are not detectable.

For comparison, in fig.8 a streakcamera photo is shown at the same initial pressure but with some CH_4 added to the Hydrogen. The oscillations are strongly damped. Magnetic probe measurements show the same effect (fig. 9).

However streakcamera photographs of the compression at 60 μ D_2 show that the behaviour of the plasma is strongly influenced by the presence of the probe. In this case the plasma diameter is comparable to the probe diameter.

With the assumption that the magnetic flux is constant during one oscillation period and with the additional assumption that the radial flow velocity of the plasma $v_r \sim \frac{r}{a}$, where a is the plasma radius, B on the axis is proportional to $\frac{1}{r^2}$ for any initial distributions of B.

Consequently a comparison of $\sqrt{\frac{B_{max}}{B_{min}}}$ with $\frac{r_{max}}{r_{min}}$ at different times of the compression should give information on the correctness of the assumptions and on flux conservation during time. This is of particular interest with regard to the reliability of probe measurements.

Fig.10 shows both B (t) on the axis and a typical side-on streak photograph of the plasma cylinder without probe. The minimum diameter of the plasma is almost constant during the oscillations. Correspondingly the maximum B field on the axis should vary only weakly.

A more quantitative analysis is shown in table I. The conclusion is that, at least for the given set of parameters and for times of about one microsecond, probe measurements are reliable.

The magnetic flux indeed is constant for the time interval from the first compression up to current maximum. Flux conservation during the first shock must still be examined.

The comparison of oscillation periods with and without probes likewise shows a remarkably good agreement. The line density is not influenced by probes. This should not be expected if heavy Fe-ions from the probe shield penetrate into the plasma at an appreciable rate.

At current maximum the value of the theoretical oscillation period agrees with the experimental value. This shows that end losses up to this time are not important.

Fig. 11 shows a densitometer plot of the streak photograph on the axis. Similar to the magnetic probe signal it reflects again the dynamic behaviour of the plasma. The values for the oscillation periods were taken from this picture. The picture gives a good demonstration for the time resolution of the camera.

At current maximum the distribution of the magnetic field in a crosssection of the coil 2 cm off the centerplane of the coil was determined. The result is shown in fig.12. For comparison a densitometer plot of the streak photograph at current maximum is shown. Probe measurements and streak photographs are taken in directions perpendicular to each other and to the coil axis. In both cases the same plasma diameter is measured, showing in addition the rotational symmetry of the plasma. The measured distribution of the magnetic field can be explained partly by the initial distribution of the magnetic field initially frozen in and partly by penetrating external fields.

The magnetic field on the axis agrees within the limits of accuracy of the measurement with the initial magnetic field on the axis multiplied by the compression ratio. This shows that the magnetic flux in the region near the axis is conserved during the whole compression and in particular during the first shock.

The magnetic field distribution has also been measured under the same experimental conditions with a probe of 4 mm total diameter. This result together with the B (t) curve on the axis is shown in fig.13. The comparison with the 1 mm probe measurements demonstrates the influence and the significance of the probe diameter.

In the pressure balance equation in the general case the external magnetic pressure is balanced by the internal magnetic pressure, the kinetic pressure, pressure due to rotation of the plasma and other inertial effects. At current maximum the latter can be neglected.

The reproducibility of the measurements and the observed rotational symmetry of the plasma cylinder argue against a fast rotation of the plasma. Furthermore a probe inserted radially into the plasma should strongly influence the azimuthal flow of the plasma. Streak photos however showed no influence of the probes. Therefore the contribution of a pressure due to plasma rotation should be small.

The kinetic pressure may contain a contribution from an eventual turbulence. This plasma turbulence should be connected with fluctuating magnetic fields. Therefore a magnetic probe, very sensitive for radial magnetic fields should be a good indicator for plasma turbulence. In our case no radial magnetic fields were measured up to the cutoff frequency of the probe, which is about 10 Mcs/sec.

With the assumption that the external magnetic pressure is balanced by the kinetic pressure plus the internal magnetic pressure one can calculate the ß of the plasma. In our experiment the ß in the vicinity of the axis is at least 0·8 and probably higher, if one takes into account that the axis of the magnetic probe does not intersect the axis of the plasma cylinder, the deviation being about 1 mm.

With the particle density being known from the measurement of the line density and the plasma radius one obtains for the temperature $T_e + T_i \approx 2 \cdot 10^6$ ^{o}K.

Numerical calculations of H. Kever (6), based on the snow plough model with the additional assumption of an initial parallel field, show that a particle energy of 0·14 keV can be expected after the first shock. This value is close to the experimental value, showing that the plasma is predominantly heated up by the first shock.

The general result of these experiments is with the given initial parameters that a stable high ß plasma can be produced reproducibly for the half period time of the bank with densities of about $3 \cdot 10^{17}$ per ccm and a temperature of about $2 \cdot 10^{6}$ °K.

Further measurements will be concerned mainly with the behaviour of a plasma with an initial reverse field while the other experimental parameters are the same.

Acknowledgements:

It is a pleasure to acknowledge many helpful discussions with Drs. Fay, Jordan and Kever. I furthermore have to thank Prof. Fucks for his continuous interest and support. Technical assistance of Mr. Korr, Mr. Braune and Mr. Bach is gratefully acknowledged.

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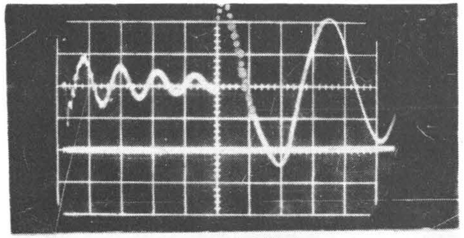
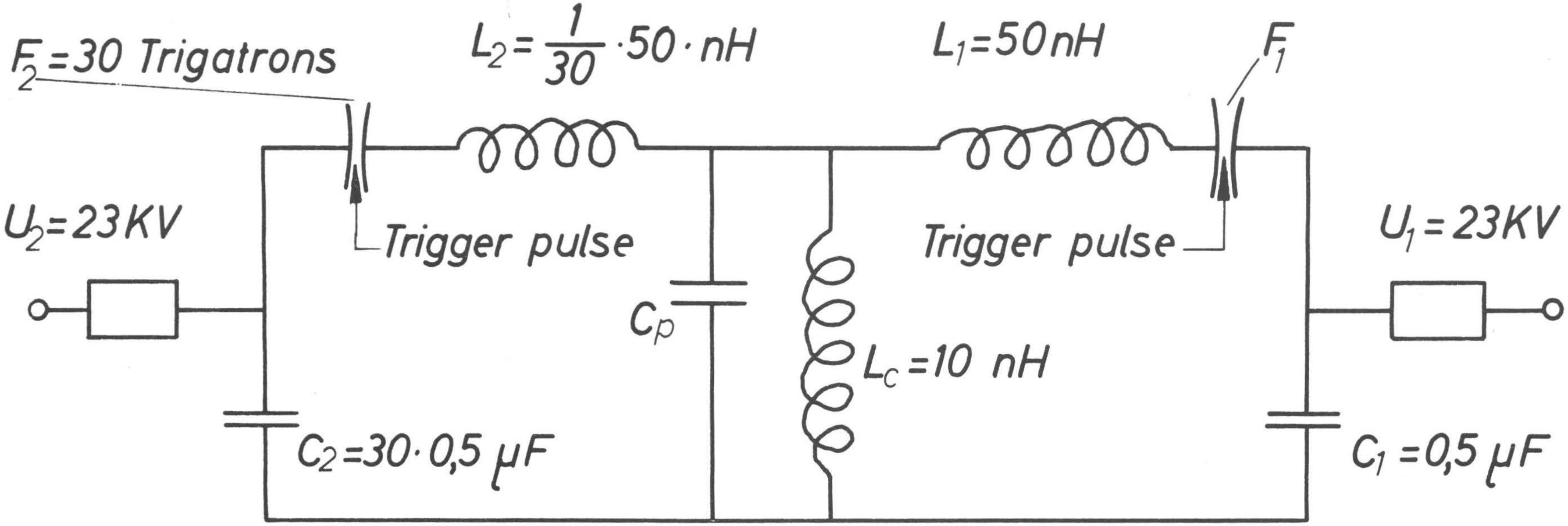


Voltage at the coil

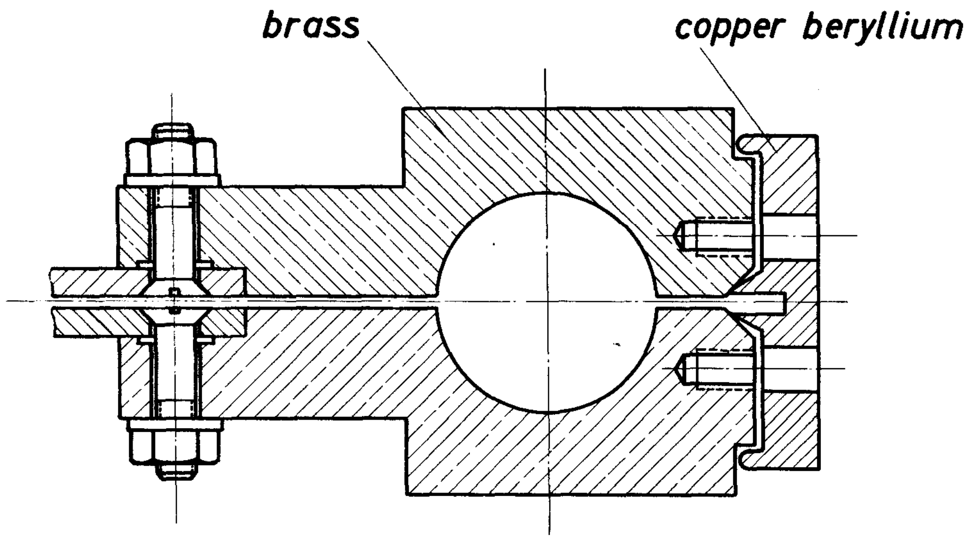


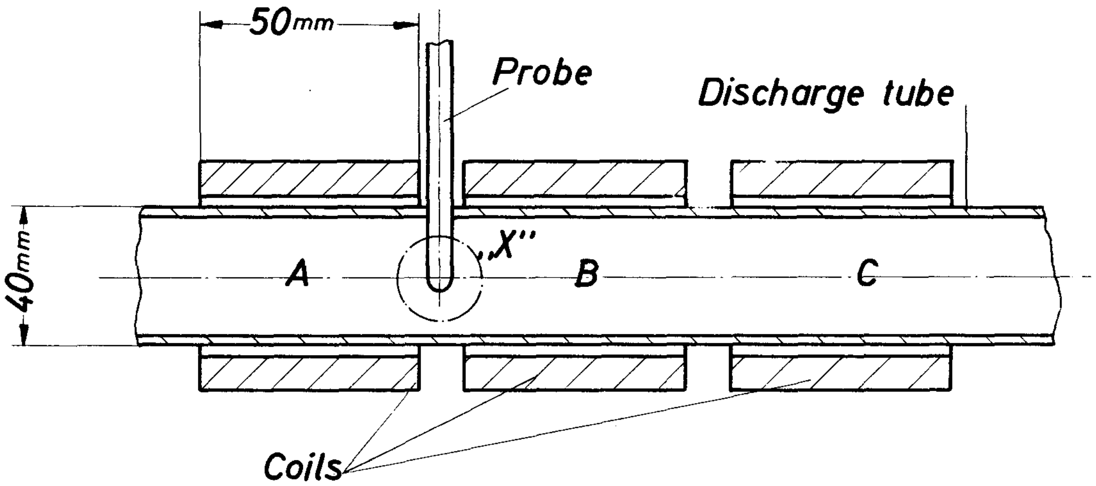
C_p = Capacitance of collector-plate

L_c = Inductance of Compression Coil

Fig.1 Electrical circuit diagram

Coil geometry





The coil consists of three interchangeable parts (ABC)
Magnetic field measurements have been made with the following set-ups:

I. According to the above illustration (inside position)

II. „A" is placed beside „C", the probe stays in the old position (end position)

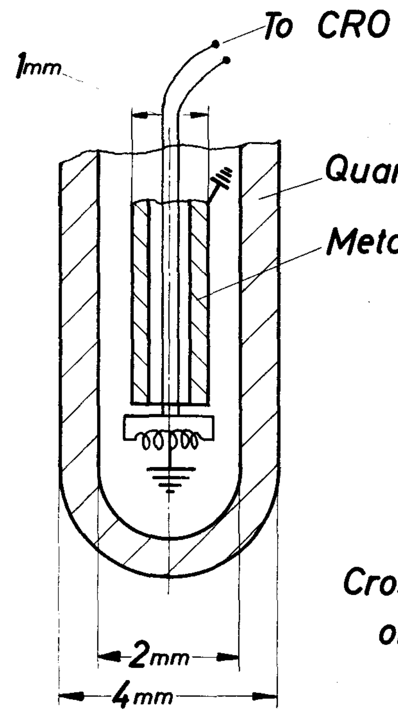
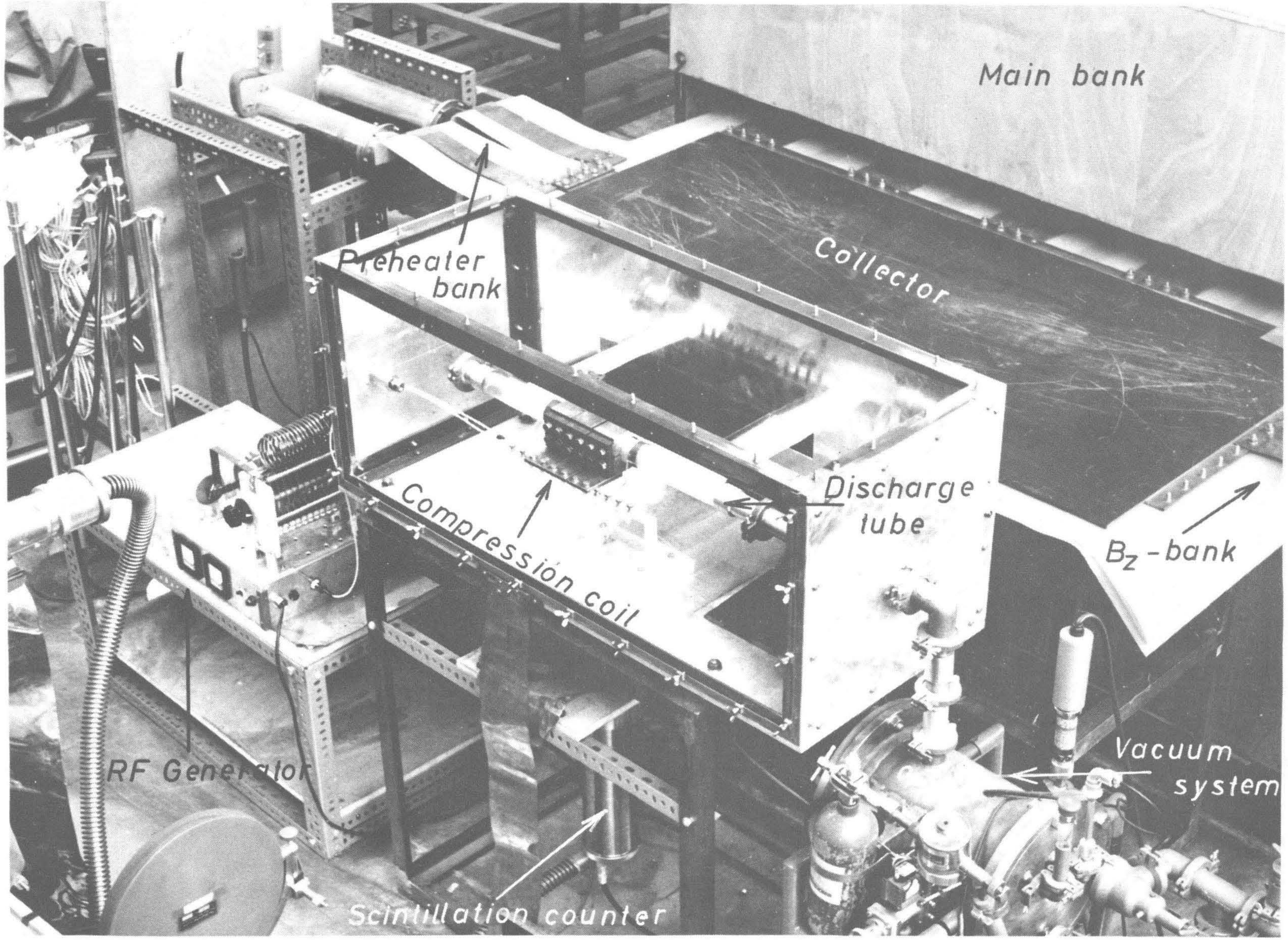
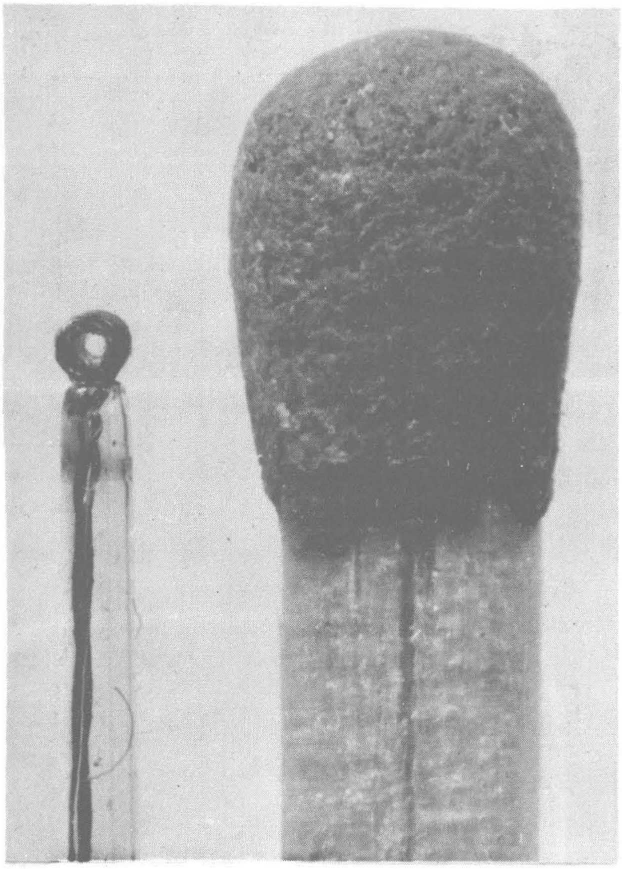


Fig. 2

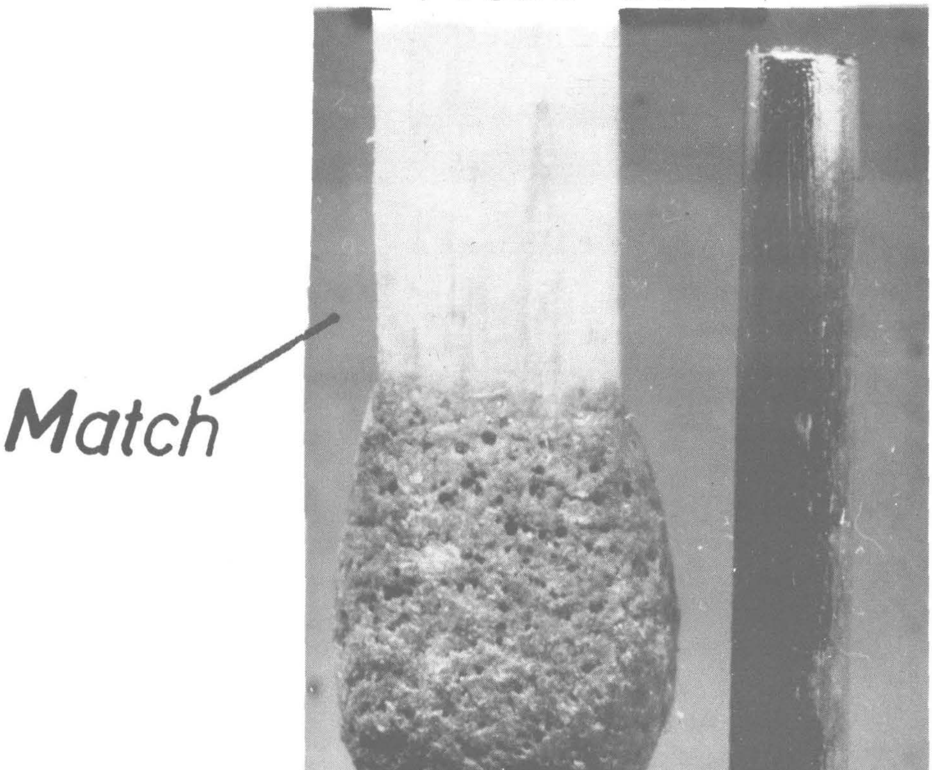


Total view of the experiment.

Fig. 3

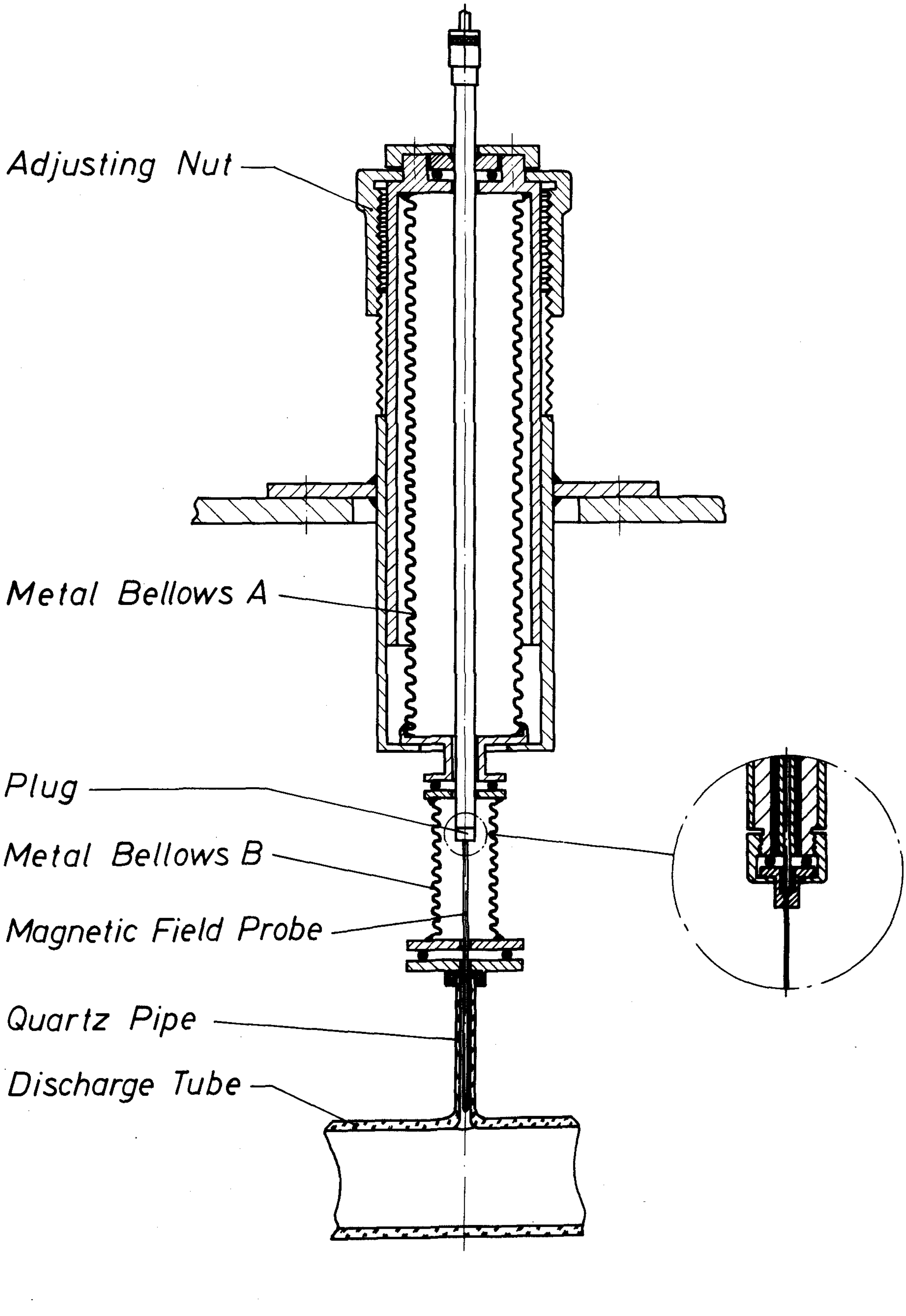


Probe coil



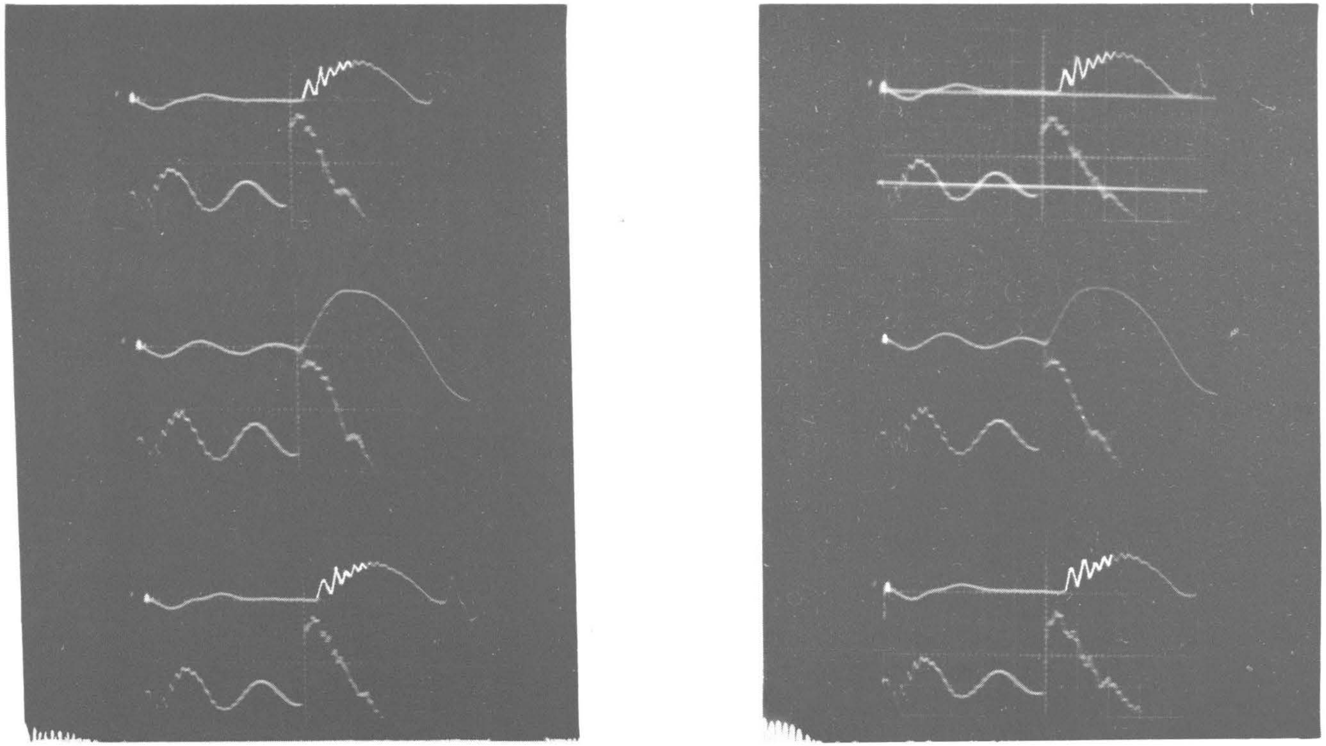
Steel shielded probe

Fig.4



Probe Adjusting Device

Fig.5



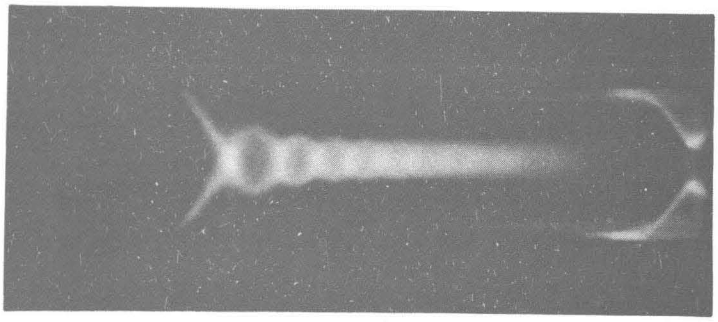
Probe Signal
Voltage at the Coil

Discharge in
Vacuum

time scale: 0,5 μ sec/div
Pressure : 250 μ D_2

Reproducibility of the Discharge
Magnetic probe signal 1mm off the axis at
different days.

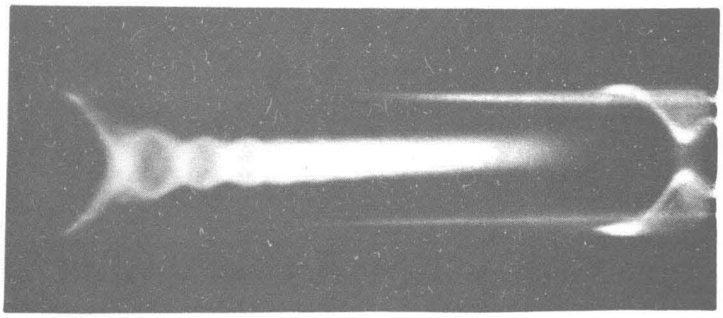
Fig. 6



$p = 250\mu D_2$.

1 μ sec

End on Streakphoto with probe.



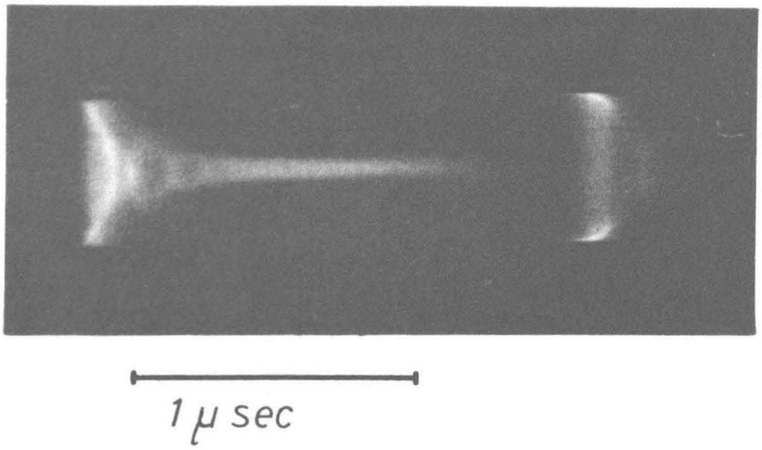
$p = 250\mu D_2$.

1 μ sec

End on Streakphoto without probe.

Influence of Magnetic Field Probe on the Plasma.

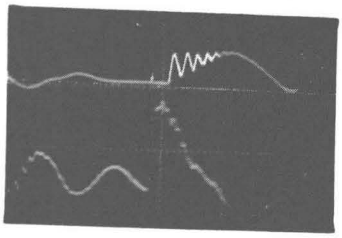
Fig. 7



$p_0 = 250\mu$ $H_2 + 1\%\ CH_4$

Streakphoto of Plasma Compression with Added Impurities.

Fig. 8

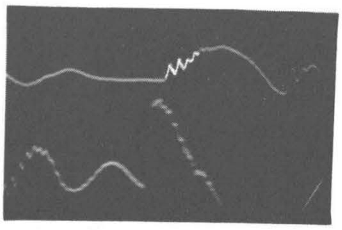


Internal B - Field

Voltage at the Coil

0,5 μ sec/Div

B on the axis at 250 μ D_2



Internal B - Field

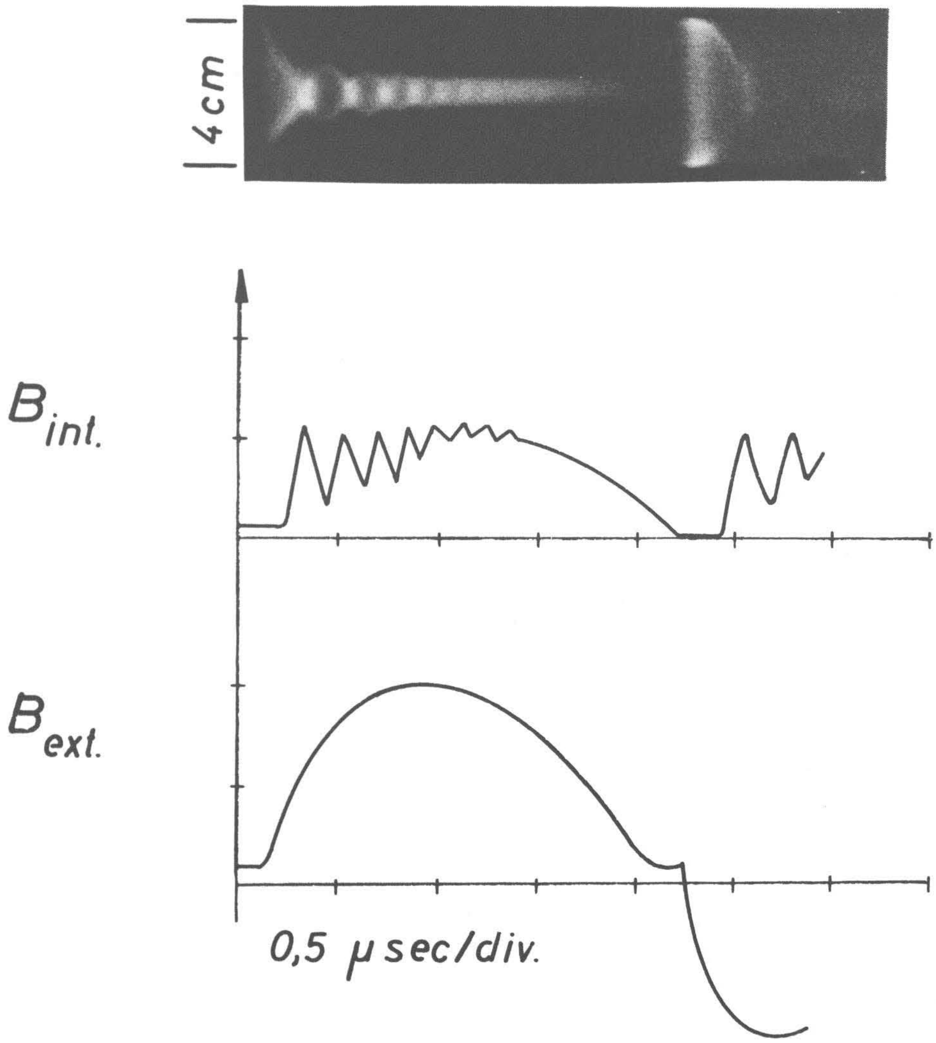
Voltage at the Coil

0,5 μ sec/Div

B on the axis at 250 μ $H_2 + 1\% CH_4$

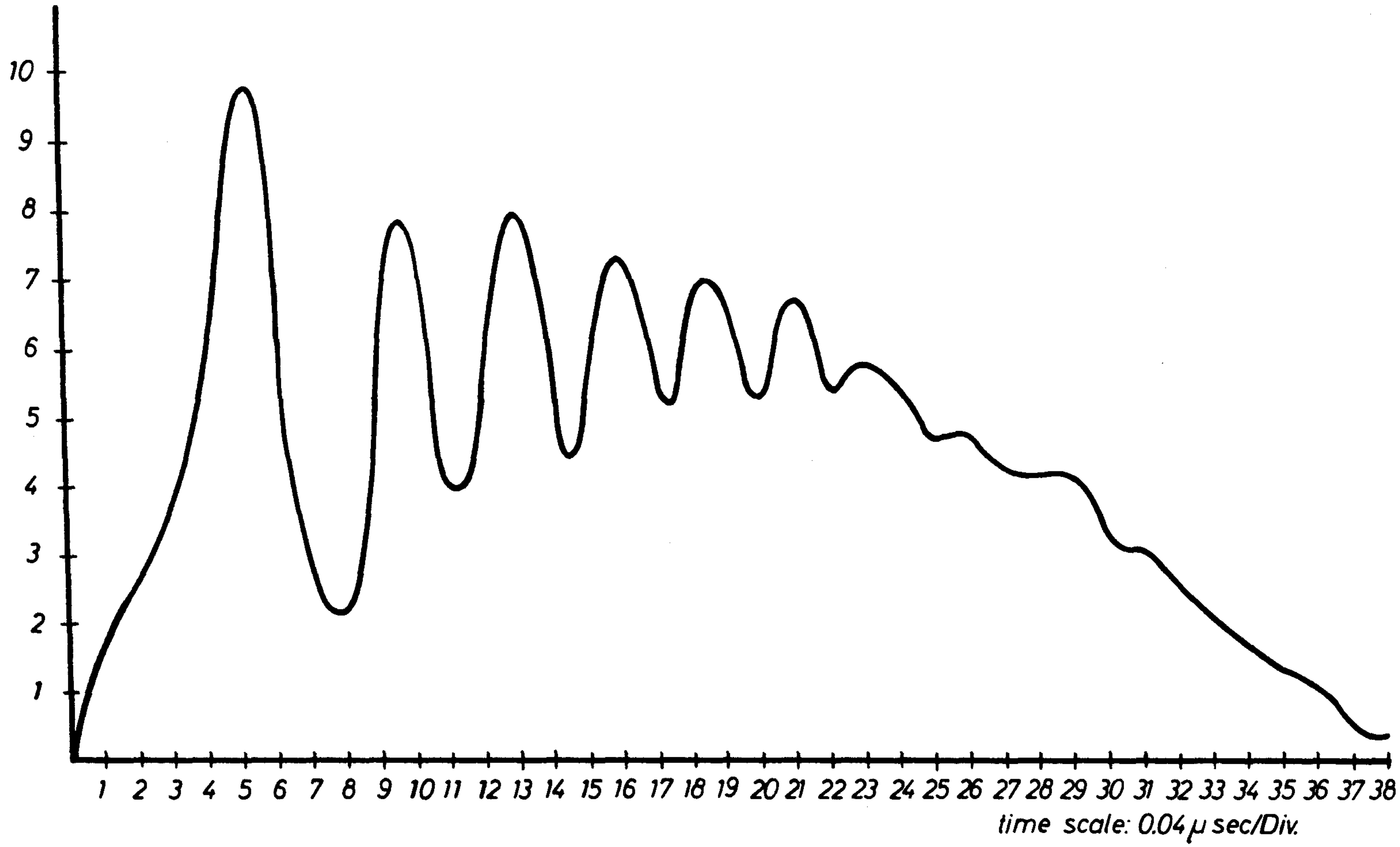
Influence of Impurities on Probe Signal

Fig. 9



Streakphoto of plasma compression, $B_{int.}(t)$ and $B_{ext.}(t)$ at an initial line density of $N_0 = 1{,}8 \cdot 10^{17}\ cm^{-1}$ and an initial magnetic field of $B_0 = 900$ Gauss.

Fig. 10



Film density on the tube axis as a function of time

$p = 250\,\mu.\,D_2$

Fig.11

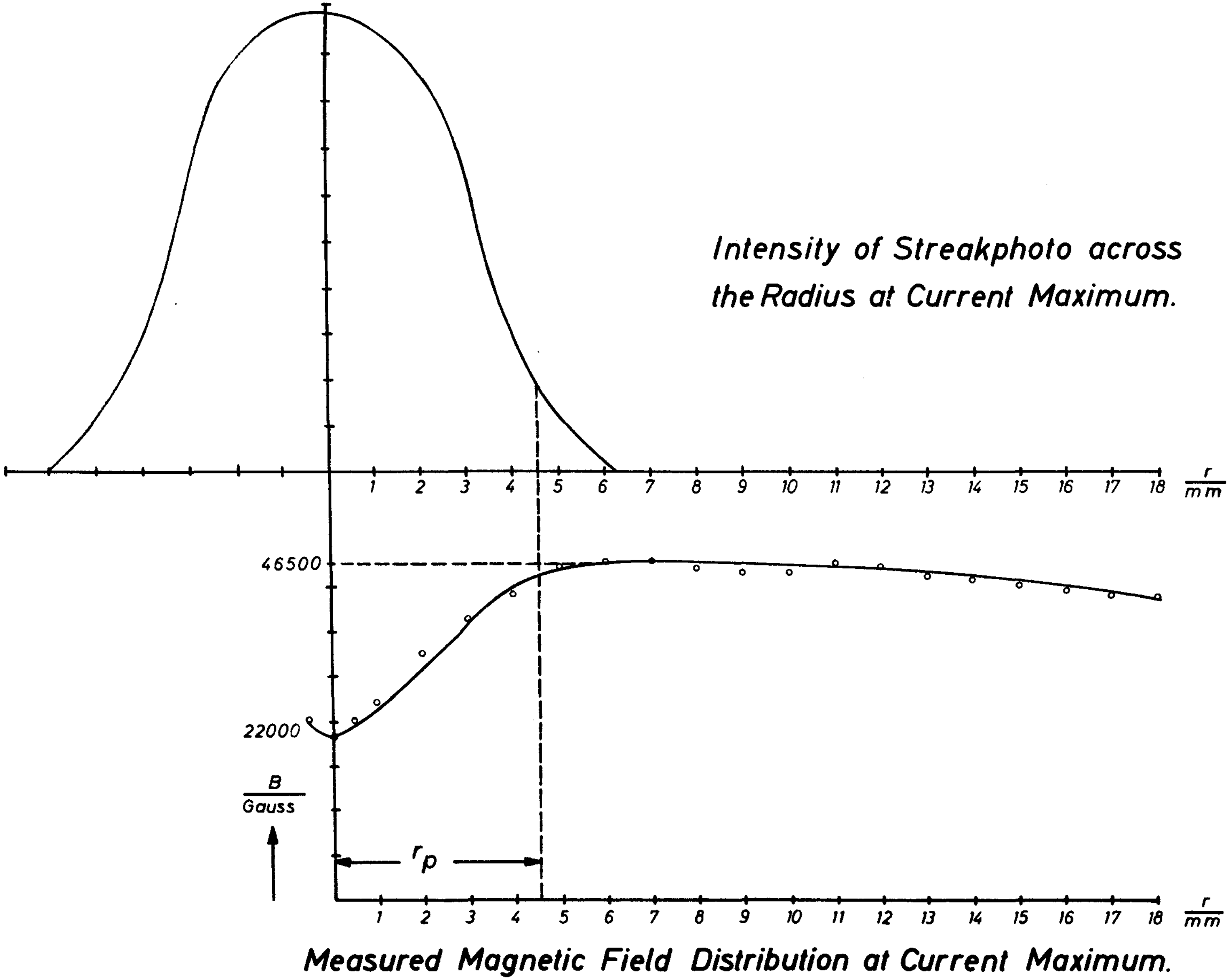
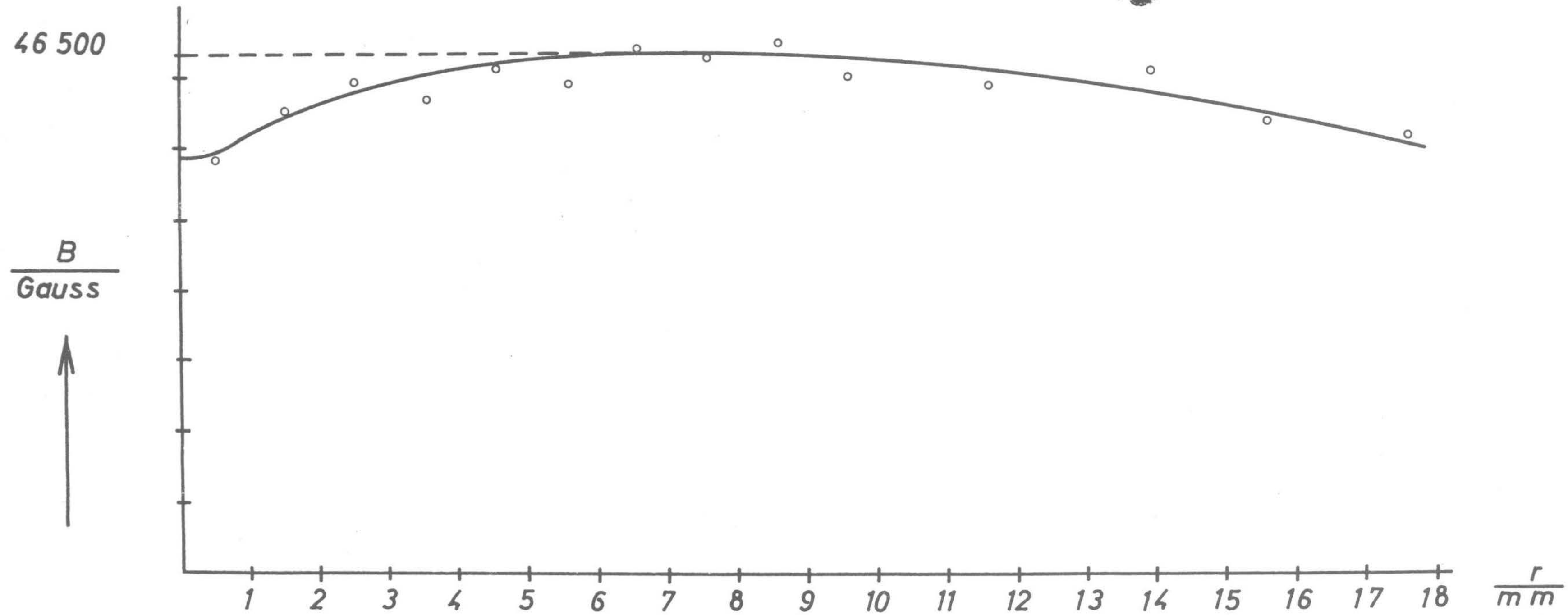


Fig.12

Plasma Radius measured with
Streak-Camera and Magnetic
Field Probe.



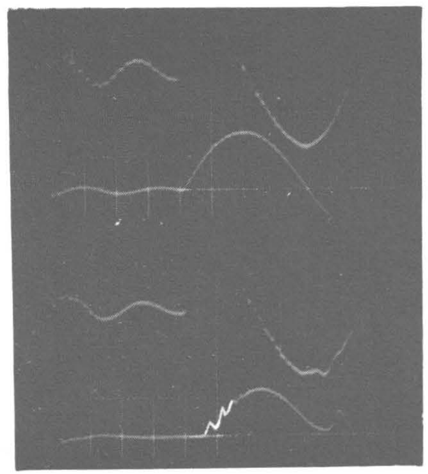
Magnetic Field Distribution at Current Maximum, measured with 4 mm Probe.

Fig.13

0,5 μsec/Div.; $2{,}5 \cdot 10^4$ Gauss/Div.

B(t) on the axis;

measured with 4 mm Probe.



Vacuum Field

p = 250 μ D_2

Internal B_z-Field

1	2	3	4	5	6
$r_{min.}$ [arbitrary units]	$r_{max.}$ [arbitrary units]	$\frac{r_{max.}}{r_{min.}}$	$B_{max.}$ [arbitrary units]	$B_{min.}$ [arbitrary units]	$\sqrt{\frac{B_{max.}}{B_{min.}}} = \frac{r_{max.}}{r_{min.}}$
4,0	7,6	1,9	4,4	1,2	1,9
4,0	5,8	1,9 1,45	4,5	2,2	1,95 1,45
3,8	4,6	1,5 1,2	4,5	3,1	1,45 1,2
3,6	4,3	1,3 1,2	4,7	3,7	1,25 1,15
3,5	4,0	1,2 1,15	4,8	4,2	1,15 1,1

Variation of $\frac{r_{max}}{r_{min}}$ with Time, measured with Streak-Camera and Magnetic Field Probe independently.

1	2	3
$\tau_C \cdot 10^{-7}$ sec	$\tau_M \cdot 10^{-7}$ sec	$\tau_{Theor.} \cdot 10^{-7}$ sec
1,8	1,85	
1,45	1,5	
1,25	1,4	
1,1	1,15	
1,0	1,05	1,07

τ_C: Oscillation period measured with Streak-Camera.

τ_M: Oscillation period measured with magnetic field probe

Variation of the Oscillation Period of the Plasma, measured with Streak-Camera and Magnetic Field Probe independently.

Table I